Exploring DDESB Acceptance Criteria for Containment of Small Charge Weights

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Abstract

This paper examines DDESB acceptance criteria for the design of structures housing small quantities of explosive materials (i.e., less than 10 lb TNT equivalent). From experience, following current DDESB design guidelines (e.g., UFC 3-340-02) can result in extremely fortified construction, in terms of wall and roof thickness and level of reinforcement, even when charge weights are small or significant venting is provided. This issue is particularly evident when small volume storage rooms are desired. Means of possibly reducing the rigidity of the current reinforced concrete acceptance criteria are explored by optimizing computational models with various construction layouts (e.g., different wall thicknesses and flexural/non-flexural reinforcement requirements) subject to shock and gas loading. Recommendations and limitations are provided for using small charges in containment applications.

1.0 Introduction

The main purpose of the current study is to illustrate that particular requirements established in Unified Facilities Criteria (UFC) 3-340-02[1] can significantly alter the design of a containment cell for small charges when compared to the construction needed for adequate flexural response. The procedures in UFC 3-340-02 are also shown to potentially lead to excessive non-flexural reinforcement for the representative cases of a 2-lb and 8-lb TNT charge.

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[1] US Department of Defense, UFC 3-340-02 (TM5-1300), "Structures to Resist the Effects of Accidental Explosions," December 2008.

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14. ABSTRACT
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This study considers a small explosive charge (i.e., <10 lb TNT equivalent) to be stored within a 15 ft × 10 ft × 15 ft high reinforced concrete room. The charge can be located as close as 2 ft away from any wall and 3 ft off the floor slab. The room is to be vented with a 14 ft × 9 ft lightweight panel not to exceed 5 psf. Initial trials considered the vent panel taking up the majority of one of the short (10 ft × 15 ft) walls, as shown in Figure 1. In this configuration, the long (15 ft × 15 ft) walls and roof slab were modeled as fixed on three sides and free along the edge adjacent to the vent panel. The remaining short wall was modeled as fixed on all four sides. Entry doors and their related effect to the surrounding wall elements were not evaluated in this study.
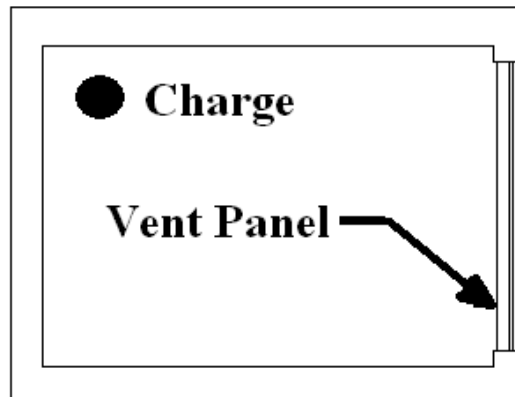

Figure 1. General Room Layout

2.0 Material Properties and Blast Loads

The reinforced concrete walls and roof were taken as Type I sections as defined in UFC 3-340-02. The concrete compressive strength was taken as 4000 psi. The minimum clear cover to the top reinforcement layer was 1-½ inches on both faces. Appropriate average and dynamic increase factors were applied to the concrete and 60,000 psi reinforcing steel depending on standoff from the target surface (i.e., close-in vs. far range). Support rotations were limited to 2 degrees.

Design blast loads acting on the walls and roof were generated using the computer programs SHOCK[2] and FRANG[3]. In SHOCK, loads were conservatively applied over reduced 4 ft × 9 ft areas and all faces of the room, including the vent panel, were taken as reflection surfaces. Per common practice, a 20% increase factor was applied to all four design charge weights (i.e., 1 lb,

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[2] Wager, P., "SHOCK User's Manual Version 1.0," NAVFAC UG-2065-SHR, April 2005.

[3] Wager, P., Connett, J., "FRANG User's Manual," Naval Civil Engineering Laboratory, Port Hueneme, CA, May 1989.

2 lb, 4 lb and 8 lb) within each program. A representative load profile showing both the shock and gas phase acting on each surface is given in Figure 2. Sample load parameter values for a 1-lb and 8-lb charge are provided in Table 1.
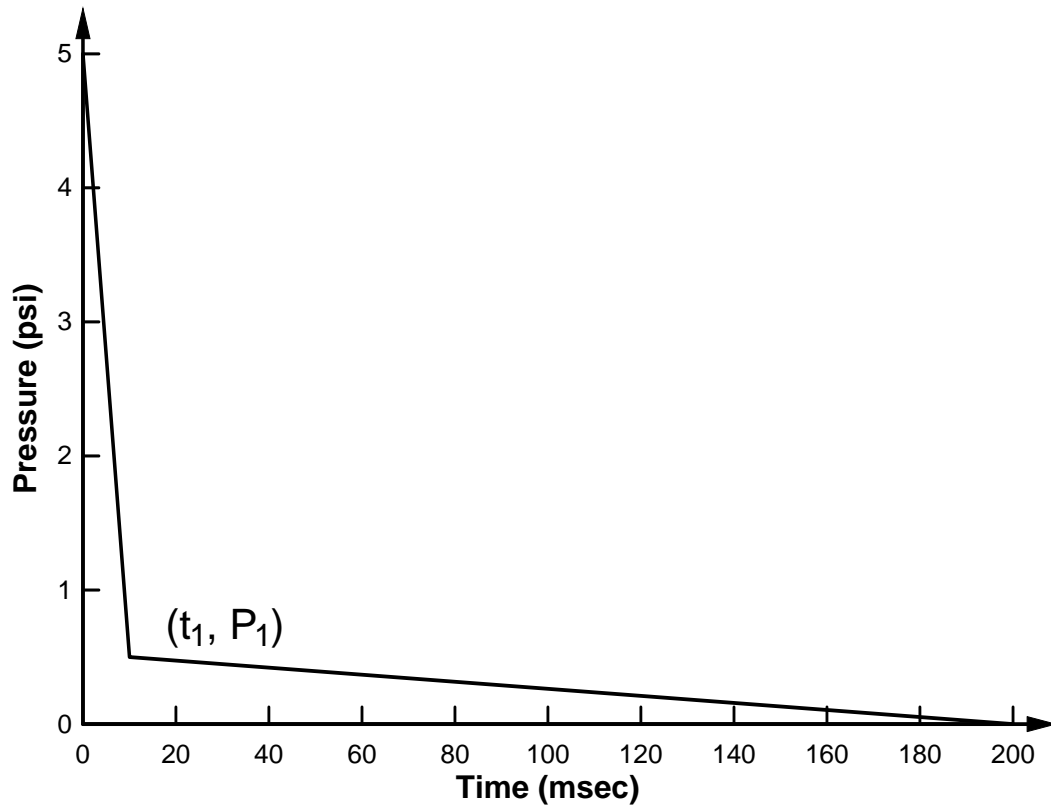

Figure 2. Representative Composite Shock and Gas Load Profile

Table 1. Representative Blast Load Parameters

Charge Size (lb)	Loading Surface	Peak Pressure (psi)	Pressure, P_1 (psi)	Time, t_1 (msec)	Duration (msec)	Impulse (psi-msec)
1	Short Wall	400	6.9	0.4	67	310
	Long Wall	380	6.9	0.4	67	300
	Roof Slab	28	6.5	4.5	67	280
8	Short Wall	2360	45	0.3	30	1060
	Long Wall	2260	45	0.3	30	1050
	Roof Slab	140	41	3.0	30	820

3.0 Determination of Required Slab Thickness and Reinforcement

The flexural response of and design reactions for each concrete component due to the four different loading scenarios were calculated with the single-degree-of-freedom program SBEDS[4]. It was determined that the long walls supported on three sides control the design for all cases. In order to meet the 2-degree rotation limit for the load from an 8-lb charge, this wall would require a thickness of 17 inches with #5 reinforcement spaced 8 inches apart on each face and in both directions. Alternatively, a 14-inch thick long wall could be used with #6 reinforcement spaced 8 inches apart. For a 4-lb charge, the long wall could be 14 inches thick with #4 reinforcement at 8 inches on center or 11 inches thick with #5 reinforcement at 8 inches on center. Finally, a 9-inch thick wall with #4 reinforcement at 8 inches on center could be used for either a 1-lb or 2-lb charge. Note that all flexural reinforcement specified in this paper are implied to be acting on each slab face and in both directions unless otherwise noted.

While these wall thicknesses and reinforcement layouts would prevent spalling and account for the space necessary for stirrups (required for close-in explosions with scaled distances less than 3 ft/lb$^{1/3}$), the thicknesses are generally inadequate to supply $d/2$ stirrup spacing as required by UFC 3-340-02. In order to meet this stirrup spacing requirement, where a single stirrup would be applied to each primary reinforcement bar as shown in Figure 3, all reinforced concrete elements would need to be over 14 inches thick for 6-inch primary reinforcement spacing and over 18 inches thick for 8-inch primary reinforcement spacing regardless of the actual reinforcement bar sizes. Taking into account that #5 bars at 8-inch spacing would be necessary within an 18-inch slab to meet minimum primary reinforcement ratio requirements and that an induced moment must be allowed to transfer between adjoining slabs to ensure a fixed boundary condition, generally all wall and roof slabs would need to be at minimum 19 inches thick with #5 reinforcement at 8 inches on center or 15 inches thick with #4 reinforcement at 6 inches on center. The only exception would be for the case of an 8-lb charge, where a 15-inch slab would not allow for an acceptable flexural response. As the short wall and roof responses would generally be much less than that of the long wall for a given charge weight, the stirrup spacing requirement appears to lead to a very inefficient design, particularly for charges less than 8 lb.

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[4] US Army Corps of Engineers, "User's Guide for the Single-Degree-of-Freedom Blast Effects Design Spreadsheets (SBEDS)," PDC-TR 06-02 Rev 1, September 2008.
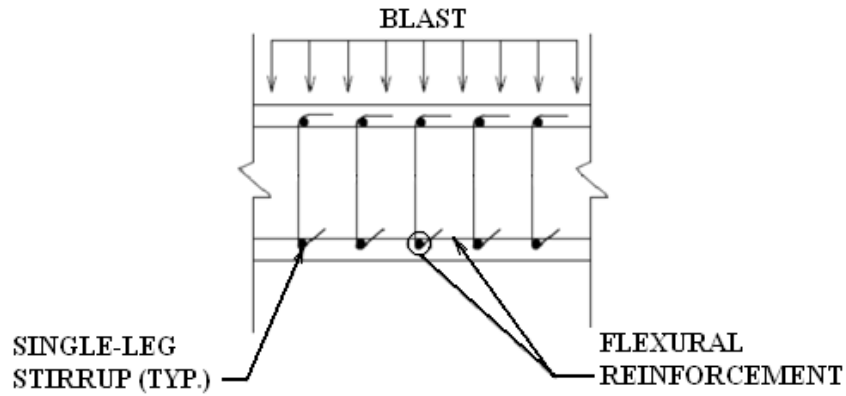
Figure 3. General Placement of Stirrups and Flexural Reinforcement

Besides stirrups for general shear control, UFC 3-340-02 requires additional steel to prevent direct shear failure (i.e., cracking) of the element and to support the tension induced from adjoining slabs responding to the internal blast load. For the former control, diagonal bars should be added as shown in Figure 4. In order to sustain the induced tension, UFC 3-340-02 suggests distributing tension reinforcement along the centerline of the element. However, so as to avoid potential over-reinforcement of the slab (and increased shear loads to be sustained by larger stirrups or diagonal bars), the approach in UFC 3-340-01[5], which combines the flexural and tension reinforcement, is applied in the current study.
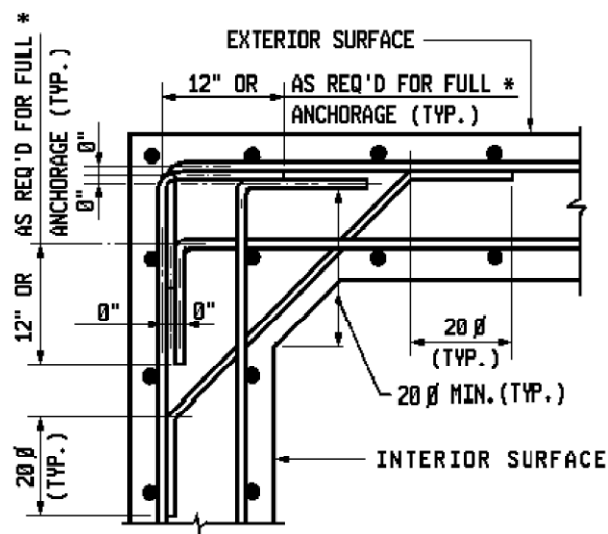

Figure 4. General Placement of Diagonal Steel Reinforcement

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[5] US Department of Defense, UFC 3-340-01 (TM 5-855-01), "Design and Analysis of Hardened Structures to Conventional Weapons Effects," June 2002.

Table 2 provides a summary of the required flexural and tension steel for the representative cases of a 2-lb charge surrounded by 15-inch thick wall and roof elements and an 8-lb charge surrounded by 19-inch elements. The "required flexural steel" column gives the reinforcement needed to achieve at most a 2-degree support rotation. Notice that only the long wall subject to an 8-lb charge blast requires #5 reinforcement at the given spacing (i.e., 6-inch for a 15-inch slab or 8-inch for a 19-inch slab) for flexural response. No other cases need more than 0.12 in^2 for the given spacing. Using the developed reactions from the required flexural steel of adjoining slabs, the required tension steel was determined in each element. In turn, half of this steel was added to the flexural steel to arrive at the required combined steel listed in Table 2. For the case of an 8-lb charge, the recommended rebar layout provided for each element is nearly optimal. The long wall may require #3 tension bars at 8 inches on center to supplement the flexural steel, but this addition may be deemed unnecessary upon using a more refined analysis (e.g., finite element) approach. In contrast, the design for the 2-lb charge appears to be quite inefficient in that #3 bars at 6 inches on center would be sufficient to carry the necessary flexure and tension loads. However, #3 bars would not be used as #4 bars are required to meet minimum primary reinforcement requirements and are preferred in construction. Note that #4 bars at greater spacing would violate the *d/2* stirrup spacing requirement. Also, note that failure to combine the required flexural and tension steel would assuredly result in additional supplemental tension steel (i.e., beyond that for the 8-lb charge case long wall) at the centerline of each element. Varying design parameters (e.g., concrete compressive strength) would generally not change this conclusion.

Table 2. Recommended Combined Flexural and Tension Reinforcement

Charge Size (lb)	Loading Surface	Required Flexural Steel (in²/in)	Critical Reaction (lb/in)	Required Tension Steel (in²/in)	Required Combined Steel (in²/in)	Recommended Rebar Spacing (on each face and in each direction)
2	Short Wall	0.027/6	570	0.047/6	0.051/6	#4@6" o.c.
	Long Wall	0.056/6	420	0.034/6	0.077/6	#4@6" o.c.
	Roof Slab	0.028/6	580	0.048/6	0.052/6	#4@6" o.c.
8	Short Wall	0.12/8	2210	0.25/8	0.24/8	#5@8" o.c.
	Long Wall	0.24/8	1810	0.20/8	0.34/8	#5@8" o.c. w/#3 (min.) tension bars
	Roof Slab	0.11/8	2260	0.24/8	0.235/8	#5@8" o.c.

Table 3 provides a summary of the required diagonal steel for the same representative 2-lb and 8-lb charge cases used in Table 2. The developed reactions from the recommended (or physical) combined flexural and tension steel lead to the use of #6 diagonal bars at 6-inch spacing around the perimeter of the short wall for the 2-lb charge case, #8 diagonal bars at 8-inch spacing for the 8-lb charge case. Required diagonal bars between the long wall and roof can be one bar size smaller at similar spacing for each case. When examining the necessary diagonal rebar based on only the "required combined steel" column from Table 2, only the diagonal bars for the small wall reduce for the 8-lb charge case. Again, this lack of significant change indicates that the recommended rebar layout provided for each element of the 8-lb charge case is nearly optimal. In contrast, the design for the 2-lb charge case again appears to be quite inefficient in that #3 diagonal bars at 6 inches on center would be sufficient to prevent cracking for all elements, but over triple the diagonal steel area is recommended per the procedures in UFC 3-340-02. Reductions in required non-flexural steel should be permitted so as to not produce an overly robust containment construction for small charges.

Table 3. Recommended Diagonal Reinforcement

Charge Size (lb)	Loading Surface	Critical Reaction (lb/in)	Req'd Diagonal Steel (in²/in)	Recommended Diagonal Rebar Spacing	Critical Reaction Based on Req'd Combined Steel (lb/in)	Diagonal Rebar Spacing Based on Req'd Combined Steel
2	Short Wall	3070	0.36/6	#6@6" o.c.	800	#3@6" o.c.
	Long Wall	1900	0.22/6	#5@6" o.c.	730	#3@6" o.c.
	Roof Slab	2520	0.29/6	#5@6" o.c.	650	#3@6" o.c.
8	Short Wall	4680	0.73/8	#8@8" o.c.	3630	#7@8" o.c.
	Long Wall	3360	0.52/8	#7@8" o.c.	3170	#7@8" o.c.
	Roof Slab	3840	0.60/8	#7@8" o.c.	2910	#7@8" o.c.

Note that the recommended combined flexural and tension reinforcement provided in Table 2 would result in #3 stirrups at 6-inch spacing for all wall and roof elements of the 2-lb charge case, and #4 stirrups at 8-inch spacing for all wall and roof elements of the 8-lb charge case. Without the slab thickness increases to meet the *d/2* stirrup spacing requirement, critical shear

loads would decrease substantially, particularly for the 2-lb charge case. Correspondingly, the available slab shear capacities would increase, resulting in only minimum stirrups being required for wall elements subject to close-in loading. Roof slabs would not require any stirrups.

Regarding the roof slabs, these elements generally deflect very little (i.e., less than a 0.2-degree support rotation) to the applied blast loads for small charges, particularly when slab thicknesses are increased well beyond flexural need to meet other requirements. While it may be theoretically possible to reduce the strength of the roof slab to gain a more efficient design, the walls would still need to adequately transfer moment across their interface with the roof to ensure fixity. An alternative approach for better efficiency would be to move the vent panel from one of the walls to the roof. Indeed, in this study the short wall has identical dimensions to the roof slab (i.e., 15 ft × 10 ft), so net blast loads would be comparable to those given in Table 1 with a full area vent panel in the roof. Reactions at the wall interfaces may increase in this approach, as would deflections of the three-side supported short walls, but an overly thick and overly reinforced roof slab would be removed. Note that service load requirements or debris hazard concerns may preclude this approach. As such, applicability would need to be evaluated on a case-by-case basis, but should at least be considered for contained charges less than 8 lb.

4.0 Conclusions

Per the study conducted, the following conclusions can be made:

- For small charge weights, wall thickness and reinforcement layout can often be dictated by issues other than flexural system response, particularly minimum stirrup spacing requirements per UFC 3-340-02. Increasing the section sizes per these requirements can result in substantially increased shear loads, which will lead to larger than otherwise necessary stirrups and diagonal bars.

- Tension reinforcement should be combined with flexural reinforcement when doing so will result in a reduction of total steel area. Following this guidance can eliminate unnecessary additional tension steel and also limit potentially excessive stirrup and diagonal bar sizes.

- The use of a full area roof vent should be considered as a means of possibly avoiding excessive roof thicknesses. However, other issues, such as service load requirements, may ultimately drive the final location of the venting surface and design of the roof.

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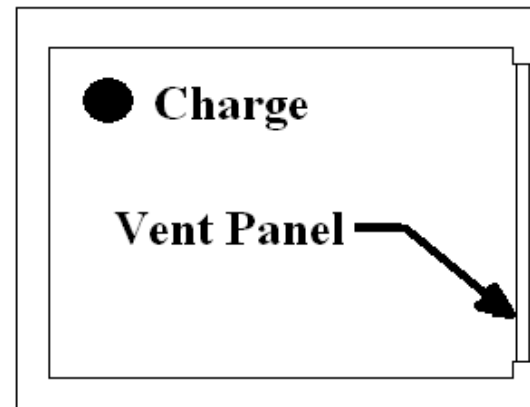
Jason R. Florek, Ph.D.
34th DDESB Seminar
13 July 2010

Problem Set-Up

- Small charge (<10 lb TNT equivalent)
- Room size (15 ft x 10 ft x 15 ft high)
- Charge located minimum 2 ft off wall and 3 ft off floor
- Lightweight vent panel (<5 psf)
- Vent area (single wall and/or roof)

Representative room layout with charge located near wall

● Charge

Vent Panel →

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Blast Load Generation

▸ SHOCK
  ◦ Load applied over reduced area
  ◦ Reflection on all surfaces
▸ FRANG

Charge Size (lb)	Loading Surface	Peak Pressure (psi)	Pressure, P_1 (psi)	Time, t_1 (msec)	Duration (msec)	Impulse (psi-msec)
1	Short Wall	400	6.9	0.4	67	310
	Long Wall	380	6.9	0.4	67	300
	Roof Slab	28	6.5	4.5	67	280
8	Short Wall	2360	45	0.3	30	1060
	Long Wall	2260	45	0.3	30	1050
	Roof Slab	140	41	3.0	30	820

Representative blast load parameters

(t_1, P_1)
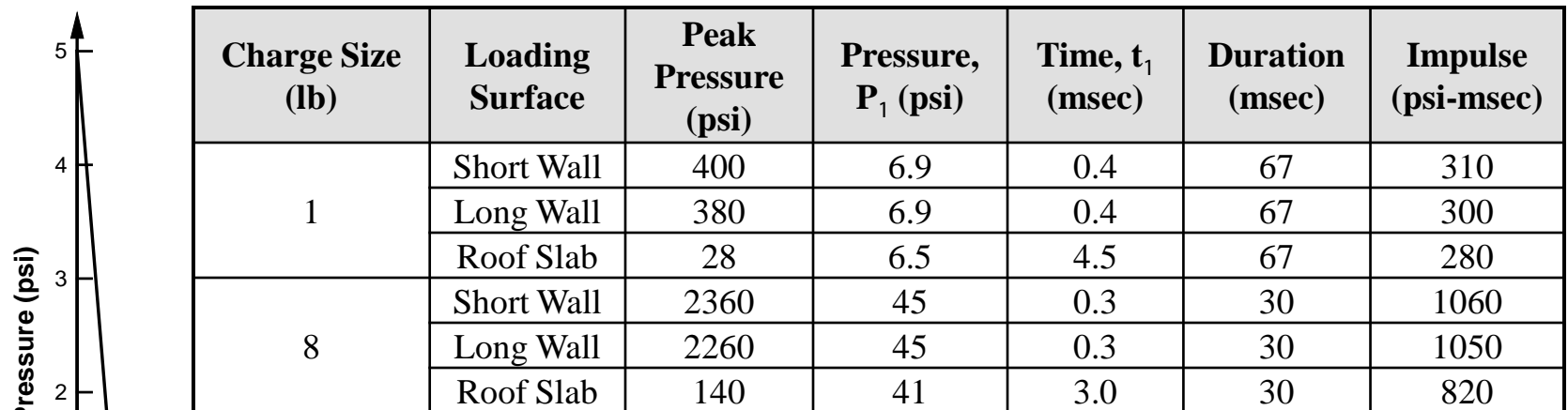
Idealized blast load shape

Pressure (psi)

Time (msec)

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Concrete Properties

- Type I section
- Limit rotation to maximum 2 degrees
- 4000 psi compressive strength
- 1-1/2" minimum clear cover
- Appropriate dynamic increase factors
  - *Stirrups required for close-in charges*

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Flexural Response (1/2)

One-Way and Two-Way Reinforced Concrete Slab

Length Along Free End, L:		15 ft
Span Along Both Sup'd Sides, H:		15 ft
Boundary Conditions:	Two-Way: Three Sides Supported - All Fixed ▼	
Response Type:	Flexural Only ▼	Type I Cross Section ▼

Structural & Material Properties

Slab Thickness, t:		17 in

Resinforcing Steel Spacing   (See diagram in cell R37 for diagram of steel input terms)

Bars Spanning Parallel to L, b_L:		8 in
Bars Spanning Parallel to H, bH:		8 in

Reinforcing Steel Areas	Inbound	Rebound	
Positive Moment Steel Parallel to L, AspL:	0.31	0.31	in^2
Negative Moment Steel Parallel to L, AsnL:	0.31	0.31	in^2
Positive Moment Steel Parallel to H, AspH:	0.31	0.31	in2
Negative Moment Steel Parallel to H, AsnH:	0.31	0.31	in2

Distance of Cover to Center of Bars: d_c

Non-Loaded Side Spanning Parallel to L:	2.3125 in
Loaded Side Spanning Parallel to L:	2.3125 in
Non-Loaded Side Spanning Parallel to H:	2.9375 in
Loaded Side Spanning Parallel to H:	2.9375 in

- SBEDS used to determine flexural response and design reactions.

Supported Weight, w:	0	psf
Concrete Density, γ:	150	lb/ft³
Poisson's Ratio, ν:	0.167	
Concrete Compressive Strength, f'c:	4,000	psi
Concrete Static Strength Increase Factor (>=1):	1.0	
Concrete Dynamic Compr. Increase Factor (>=1):	1.25	
Concrete Dynamic Compr. Strength, f'dc:	5,000	psi
Concrete Elastic Modulus, Ec:	3,834,254	psi
Select Reinforcement:	A615, A616, A706 (All Gr. 60) ▼	
Reinf. Steel Yield Strength, fs:	60,000	psi
Reinf. Steel Ultimate Strength, fu:	90,000	psi
Static Strength Increase Factor:	1.1	
Dynamic Increase Factor:	1.23	
Dynamic Reinf. Steel Yield Stress, fds:	81,180	psi
Reinf. Steel Elastic Modulus, Es:	29000000	psi
Axial Load Input:	No Dynamic Axial Load ▼	
Static Axial Load, P': (Note: Enter P>=0)	0	lb/in
Span Length in Direction of Axial Load	0	ft

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Flexural Response (2/2)

Results Summary				
θ_{max} =	1.81 deg.	Design Criteria:		LLOP/Primary
μ =	13.62		Response OK compared to input design criteria	
X_{max} Inbound =	2.85 in		at time =	26.44 msec
X_{min} Rebound =	0.00 in		at time =	0.00 msec
R_{max} =	36.85 psi		at time =	26.44 msec
R_{min} =	-25.11 psi		at time =	37.42 msec
Shortest Yield Line Distance to Determine θ:				90.0 in

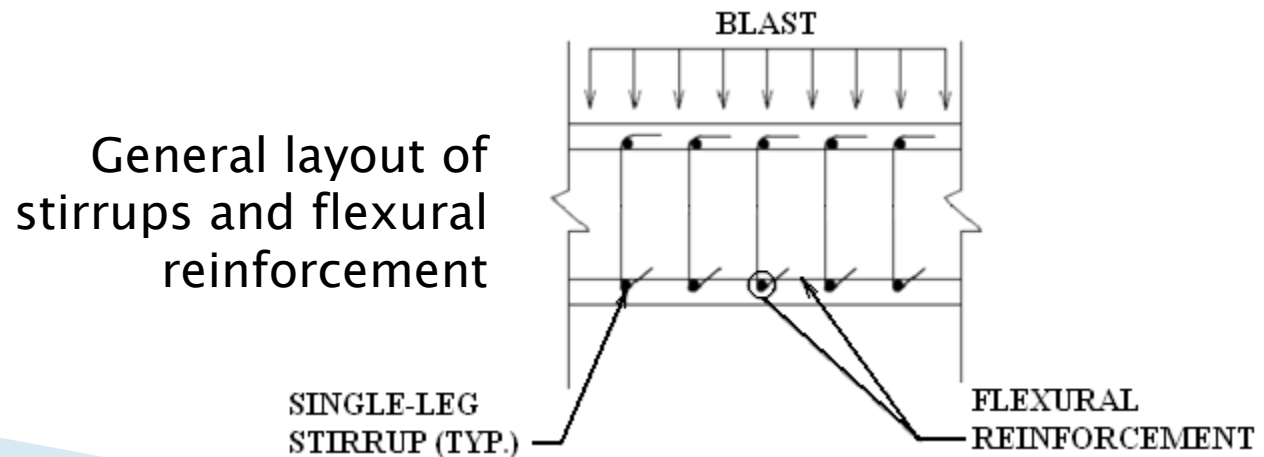| Equivalent Static Reactions*		
Peak Reactions Based on Ultimate Flexural Resistance: Vu		
Vu at supports in L direction	2,546.0	lb/in
Vu at supports in H direction	2,484.0	lb/in
Maximum Vu at distance d from support *** =	2,166.2	lb/in
Concrete Shear Capacity		
Direct Shear Capacity, (monolithic joint) $V_{c,direct}$ =	11500.0	lb/in
Diagonal Shear Capacity: $V_{c,diag}$ =	2032.9	lb/in
Tensile steel depth for shear calculations, d:	14.4	in
Results based on Max Shear Region		
At support:	Stirrups Required	
At distance d from support:	Stirrups Required	
*Required Stirrups, Av based on Max Shear Region** *		
For critical section @ support, A_{v,req_s}	0.0004	in^2/in^2
For critical section at d, A_{v,req_d}	0.0001	in^2/in^2
* Based on larger of inbound and rebound ultimate flexural resistance, not including tension or		

- SBEDS used to determine flexural response and design reactions.
- These values correspond with those obtained from UFC 3-340-02.
- Concrete shear capacity values show deviations.

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Required Wall Thickness and Reinforcement in Flexure

- 8 lb charge:
  ◦ 17 inches w/ #5@8" o.c. in both directions
  ◦ 14 inches w/ #6@8" o.c. in both directions
- 4 lb charge:
  ◦ 14 inches w/ #4@8" o.c. in both directions
  ◦ 11 inches w/ #5@8" o.c. in both directions
- 1 lb or 2 lb charge:
  ◦ 9 inches w/ #4@8" o.c. in both directions

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Design Checks (1/2)

- Generally follow guidelines in UFC 3-340-02
- Minimum horizontal and vertical reinforcement ratios $A_s = 1.875 \dfrac{\sqrt{f'_c}}{f_y} bd$
- Ultimate shear capacity and stirrups

$$v_c = 2(1 + N_u/500A_g) (f'_{dc})^{1/2} \geq 0 \qquad A_v = [(v_u - v_c)b_s s_s]/\phi f_{ds}$$

- *Stirrups to be spaced at most d/2 apart*

General layout of stirrups and flexural reinforcement

BLAST

SINGLE-LEG
STIRRUP (TYP.)

FLEXURAL
REINFORCEMENT

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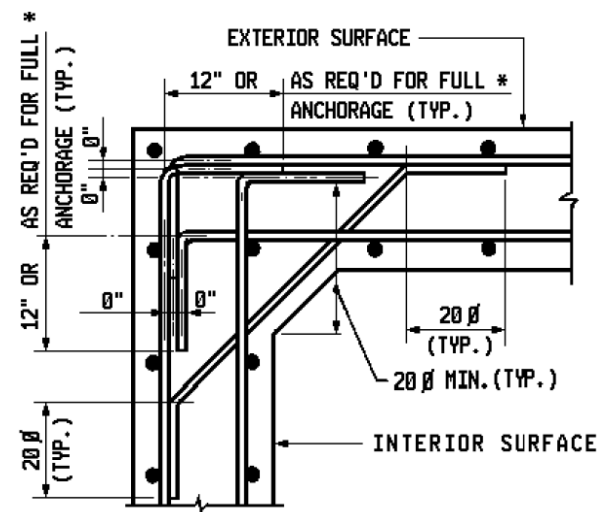# Design Checks (2/2)

- Direct shear capacity and diagonal bars

$$V_d = \quad 0 \; (\Theta > 2° \text{ or section in tension}) \qquad A_d = (V_s b - V_d)/(f_{ds} \sin(\alpha))$$

- Tension reinforcement
- Spalling

$$\frac{h}{R} = \frac{1}{a + b\Psi^{2.5} + c\Psi^{0.5}} \qquad \Psi = R^{0.926} f'_c{}^{0.266} W_{adj}{}^{-0.353} \left(\frac{W_{adj}}{W_{adj} + W_c}\right)^{0.333}$$

General layout of diagonal and flexural reinforcement

Tension Reinforcement

▸ Per Section 4-20A in UFC 3-340-02:

"In single-cell structures, unbalanced (support reactions) exist at all element intersections (walls, and floor and wall intersections) and must be resisted by tension force produced in the support elements. *In addition to the reinforcement required to resist flexural and shear stresses, tension reinforcement, distributed along the centerline of the elements, is required.*"

Required Wall Thickness to Meet Non-Flexural Guidelines

- **8 inches minimum** to fit 2 layers of #4 bar in each direction with 1-1/2" clear cover
  - **No stirrups or tension steel**
  - Charge weight must be **maximum 0.87 lb** at 2-ft standoff to meet $Z < 3.0$ ft/lb³
- **11 inches minimum to prevent spall** due to 8 lb charge (6 inches for 4 lb charge)
- **13 inches minimum to fit flexural and non-flexural steel** with adequate spacing between layers
  - Stirrups/Primary and secondary reinforcement
  - Space for concrete fill
  - Diagonal bars and tension reinforcement

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Required Wall Thickness to Meet Stirrup Spacing Guidelines

- 14+ inches minimum to allow d/2 spacing of #3 stirrups with 6-inch primary reinforcement spacing
- 18+ inches minimum to allow d/2 spacing of #3 stirrups with 8-inch primary reinforcement spacing
  - #5 bar required to meet minimum allowable primary reinforcement ratio $A_s = 1.875 \dfrac{\sqrt{f'_c}}{f_y} bd$

Required Wall Thickness and Reinforcement (Updated)

- 8 lb charge:
  ◦ **18+ inches w/ #5@8" o.c. in both directions**
  ◦ ~~17 inches w/ #5@8" o.c. in both directions~~
  ◦ ~~14 inches w/ #6@8" o.c. in both directions~~
- 4 lb charge:
  ◦ 18+ inches w/ #5@8" o.c. in both directions
  ◦ 14+ inches w/ #4@6" o.c. in both directions
  ◦ ~~14 inches w/ #4@8" o.c. in both directions~~
  ◦ ~~11 inches w/ #5@8" o.c. in both directions~~
- 1 lb or 2 lb charge:
  ◦ 18+ inches w/ #5@8" o.c. in both directions
  ◦ **14+ inches w/ #4@6" o.c. in both directions**
  ◦ ~~9 inches w/ #4@8" o.c. in both directions~~

Determination of Combined Flexural/Tension Reinforcement (1/4)

▶ Per Section 10.3.3.5 in UFC 3-340-01:

"The additional axial tension reinforcement required can be incorporated by adding it to the quantity of flexural bars equally in each face or by placing separate axial load bars at the mid-depth of the element. This procedure is conservative and may be very conservative in some cases."

Determination of Combined Flexural/Tension Reinforcement (2/4)

One-Way and Two-Way Reinforced Concrete Slab

Structural & Material Properties			
Slab Thickness, t:		19	in
Resinforcing Steel Spacing (See diagram in cell R37 for diagram of steel input terms)			
Bars Spanning Parallel to L, b_L:		8	in
Bars Spanning Parallel to H, bH:		8	in
Reinforcing Steel Areas	Inbound	Rebound	
Positive Moment Steel Parallel to L, AspL:	0.24	0.24	in^2
Negative Moment Steel Parallel to L, AsnL:	0.24	0.24	in^2
Positive Moment Steel Parallel to H, AspH:	0.24	0.24	in2
Negative Moment Steel Parallel to H, AsnH:	0.24	0.24	in2
Distance of Cover to Center of Bars: d_c			
Non-Loaded Side Spanning Parallel to L:		2.3125	in
Loaded Side Spanning Parallel to L:		2.3125	in
Non-Loaded Side Spanning Parallel to H:		2.9375	in
Loaded Side Spanning Parallel to H:		2.9375	in

‣ Flexural response of long wall to an 8 lb charge.

‣ Additional tension steel ignored.

Results Summary				
θ_{max} =	1.98 deg.	Design Criteria:		LLOP/Primary
μ =	22.76		Response OK compared to input design criteria	
X_{max} Inbound =	3.11 in		at time =	29.78 msec
X_{min} Rebound =	0.00 in		at time =	0.00 msec
R_{max} =	32.72 psi		at time =	29.78 msec
R_{min} =	-22.62 psi		at time =	39.58 msec
Shortest Yield Line Distance to Determine θ:				90.0 in
Equivalent Static Reactions*				
Peak Reactions Based on Ultimate Flexural Resistance: Vu				
Vu at supports in L direction			2,259.5	lb/in
Vu at supports in H direction			2,211.0	lb/in
Maximum Vu at distance d from support *** =			1,889.4	lb/in

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Determination of Combined Flexural/Tension Reinforcement (3/4)

One-Way and Two-Way Reinforced Concrete Slab

Structural & Material Properties			
Slab Thickness, t:		15	in

Resinforcing Steel Spacing   (See diagram in cell R37 for diagram of steel input terms)

Bars Spanning Parallel to L, b_L:		6	in
Bars Spanning Parallel to H, bH:		6	in

Reinforcing Steel Areas

	Inbound	Rebound	
Positive Moment Steel Parallel to L, AspL:	0.056	0.056	in^2
Negative Moment Steel Parallel to L, AsnL:	0.056	0.056	in^2
Positive Moment Steel Parallel to H, AspH:	0.056	0.056	in2
Negative Moment Steel Parallel to H, AsnH:	0.056	0.056	in2

Distance of Cover to Center of Bars: d_c

Non-Loaded Side Spanning Parallel to L:	2.25	in
Loaded Side Spanning Parallel to L:	2.25	in
Non-Loaded Side Spanning Parallel to H:	2.75	in
Loaded Side Spanning Parallel to H:	2.75	in

- Flexural response of long wall to a 2 lb charge.
- Additional tension steel ignored.

Results Summary				
θ_{max} =	1.95 deg.	Design Criteria:		LLOP/Primary
μ =	43.84		Response OK compared to input design criteria	
X_{max} Inbound =	3.06 in		at time =	53.06 msec
X_{min} Rebound =	0.00 in		at time =	0.00 msec
R_{max} =	7.86 psi		at time =	53.06 msec
R_{min} =	0.00 psi		at time =	0.00 msec
Shortest Yield Line Distance to Determine θ:				90.0 in
Equivalent Static Reactions*				
Peak Reactions Based on Ultimate Flexural Resistance: Vu				
Vu at supports in L direction			542.6	lb/in
Vu at supports in H direction			530.5	lb/in
Maximum Vu at distance d from support *** =			471.6	lb/in

Determination of Combined Flexural/Tension Reinforcement (4/4)

Charge Size (lb)	Loading Surface	Required Flexural Steel (in²/in)	Critical Reaction (lb/in)	Required Tension Steel (in²/in)	Required Combined Steel (in²/in)	Recommended Rebar Spacing (on each face and in each direction)
2	Short Wall	0.027/6	570	0.047/6	0.051/6	#4@6" o.c.
	Long Wall	0.056/6	420	0.034/6	0.077/6	#4@6" o.c.
	Roof Slab	0.028/6	580	0.048/6	0.052/6	#4@6" o.c.
8	Short Wall	0.12/8	2210	0.25/8	0.24/8	#5@8" o.c.
	Long Wall	0.24/8	1810	0.20/8	0.34/8	#5@8" o.c. w/ #3 (min.) tension bars
	Roof Slab	0.11/8	2260	0.24/8	0.235/8	#5@8" o.c.

Recommended rebar spacing to satisfy
flexural and tension steel requirements

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Determination of Diagonal Steel Reinforcement

Charge Size (lb)	Loading Surface	Critical Reaction (lb/in)	Req'd Diagonal Steel (in²/in)	Recommended Diagonal Rebar Spacing	Critical Reaction Based on Req'd Combined Steel (lb/in)	Diagonal Rebar Spacing Based on Req'd Combined Steel
2	Short Wall	3070	0.36/6	#6@6" o.c.	800	#3@6" o.c.
	Long Wall	1900	0.22/6	#5@6" o.c.	730	#3@6" o.c.
	Roof Slab	2520	0.29/6	#5@6" o.c.	650	#3@6" o.c.
8	Short Wall	4680	0.73/8	#8@8" o.c.	3630	#7@8" o.c.
	Long Wall	3360	0.52/8	#7@8" o.c.	3170	#7@8" o.c.
	Roof Slab	3840	0.60/8	#7@8" o.c.	2910	#7@8" o.c.

Recommended rebar spacing to satisfy diagonal steel requirements

$$A_d = (V_s b - V_d)/(f_{ds} \sin(\alpha))$$

Stirrup Requirements

- 8 lb charge:
  - #4 stirrups @8" o. c. in all wall and roof slabs
- 2 lb charge:
  - #3 stirrups @6" o. c. in all wall and roof slabs
- Without slab increase to meet stirrup spacing requirements:
  - Critical shear loads would **decrease** substantially.
  - Slab shear capacity would **increase** correspondingly.

$$v_c = 2(1 + N_u/500A_g) \, (f'_{dc})^{1/2} \geq 0$$

  - Minimum stirrups only required in walls for close–in range.

Roof Slab Design

▸ Roof slab will generally deflect much less than walls due to increased standoff.

▸ Moment capacity must be maintained to ensure fixity in walls.

▸ Vent panel in roof can potentially allow for large reduction in required materials.

▸ Other issues (e.g., service loads) could control design.

Representative room layout with charge located near wall

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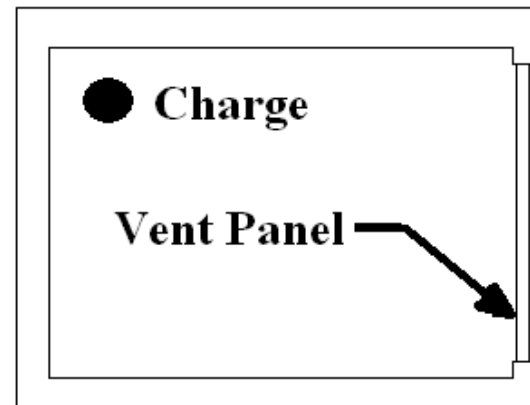
Use of CMU Walls in Containment Design

- Reinforced concrete construction generally used in containment design for explosives.
- For low pressures and impulses, other more cost-effective materials can become viable.
- Reusable CMU limited to 0.5 degree rotation per UFC 3-340-02.
- ASCE provides reinforced masonry component limits identical to R/C:
  - Low-1 degree
  - Medium-2 degrees
  - High-5 degrees

Wall Type	Support Type	Support Rotation
Reusable	One-way	0.5°
	Two-way	0.5°
Non-Reusable	One-way	1.0°
	Two-way	2.0°

Response limits for masonry walls per UFC 3-340-02

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Limitations of Using CMU Walls

- UFC response criterion can be achieved for **fully grouted**, 12" reinforced CMU walls for charges on the order of **¼ lb TNT** in a comparable room volume.
- **Larger charge sizes can be mitigated** with increased room volume, increased standoff or use of less restrictive response criterion.
- CMU-specific issues:
  ◦ Section in tension
  ◦ Additional concerns
- **Testing warranted** for small charges in various configurations.

Conclusions (1/2)

- For small charge weights, design of wall thickness and reinforcement layout can often be dictated by non-flexural requirements, particularly minimum stirrup spacing per UFC 3-340-02.
- Substantially increased shear loads can result.
- Tension reinforcement should be combined with flexural reinforcement when it is possible to reduce total steel area.
  - Can avoid unnecessary additional tension steel
  - Can limit excessive stirrup and diagonal bar sizes

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Conclusions (2/2)

- **Consider using roof vent** as a means to possibly avoid excessive roof thicknesses.
- Reinforced CMU can potentially be used in containment of small charge sizes.
- Additional CMU testing should be explored.

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Questions
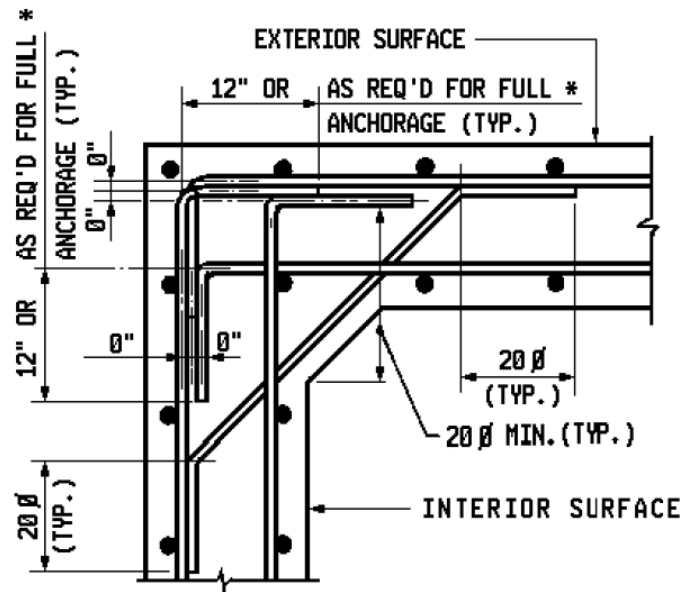
"This bar is getting crowded.
Let's get out of here."